ERDC/CRREL SR-19-3

Cold Regions Research and Engineering Laboratory

US Army Corps of Engineers®
Engineer Research and Development Center

ERDC
ENGINEER RESEARCH & DEVELOPMENT CENTER

Engineering for Polar Operations, Logistics, and Research (EPOLAR)

Analysis of Recent Support-Column Survey Results for the Elevated Facility at Amundsen-Scott South Pole Station

George Blaisdell, Jason Weale, and Lynette Barna

June 2019

Engineering for Polar Operations, Logistics, and Research (EPOLAR)

ERDC/CRREL SR-19-3
June 2019

Analysis of Recent Support-Column Survey Results for the Elevated Facility at Amundsen-Scott South Pole Station

George Blaisdell, Jason Weale, and Lynette Barna

U.S. Army Engineer Research and Development Center (ERDC)
Cold Regions Research and Engineering Laboratory (CRREL)
72 Lyme Road
Hanover, NH 03755-1290

Final Report

Prepared for National Science Foundation, Office of Polar Programs
2415 Eisenhower Avenue
Alexandria, VA 22314

Under Engineering for Polar Operations, Logistics, and Research (EPOLAR)
EP-ANT-18-06, “Program and Technical Support,” and EP-ANT-18-20,
“Engineering Support for Antarctic Facilities”

Abstract

The snow-based foundation for the large elevated Station at Amundsen-Scott South Pole Station is continuously migrating (creep) away from the load imparted by structure's support columns and grade beams. Because of nonhomogeneities in the snow foundation, differential loads on each support column, and the facility's approximately 10-year build-out and progressive-occupancy period, nonuniform settlement of columns is occurring. The created differences in the tops of the columns, where the Station's floor is attached, can cause serious structural damage and interfere with utilities.

Following up on our previous (2006) review of the history of column settlement, this report incorporates essential ancillary measurements and assesses actual Station floor levelness. We determine that past actions to mitigate differential column settlement by shimming at column tops has and continues to be adequate to maintain an acceptable floor levelness. Further, we present a model for predicting future measures of floor levelness that can help facilitate decisions about when and what columns to shim to best preserve resources.

Contents

Figures and Tables

Figures

Tables

Preface

This study was conducted for the National Science Foundation, Office of Polar Programs (NSF-OPP), under Engineering for Polar Operations, Logistics, and Research (EPOLAR) EP-ANT-18-06, "Program and Technical Support," and EP-ANT-18-20, "Engineering Support for Antarctic Facilities." The technical monitor was Mr. Michael Gencarelli, facilities construction and maintenance program manager for the U.S. Antarctic Program, NSF-OPP.

The work was performed by the Force Projection and Sustainment Branch (CEERD-RRH) of the Research and Engineering Division (CEERD-RR), U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL). At the time of publication, Mr. Justin Putnam was Acting Chief, CEERD-RRH; Mr. Jared Oren was Acting Chief, CEERD-RR; and Dr. Rosa Affleck was the program manager for EPOLAR. The Deputy Director of ERDC-CRREL was Mr. David B. Ringelberg, and the Director was Dr. Joseph L. Corriveau.

The authors also express their appreciation to Ms. Emily Moynihan for editing support and to Mr. William Johnson, Antarctic Support Contract (Leidos) 2017–2018 South Pole Station winter facilities construction manager, and Mr. John Rand, retired CRREL, for technical reviews.

COL Ivan P. Beckman was Commander of ERDC, and Dr. David W. Pittman was the Director.

Acronyms and Abbreviations

CRREL	U.S. Army Cold Regions Research and Engineering Laboratory
EPOLAR	Engineering for Polar Operations, Logistics, and Research
ERDC	Engineer Research and Development Center
NCEL	Naval Civil Engineering Laboratory
NSF	National Science Foundation
OPP	Office of Polar Programs
SPBM	South Pole Benchmark
USAP	U.S. Antarctic Program

Unit Conversion Factors

Multiply	By	To Obtain
feet	0.3048	meters
inches	0.0254	meters
square feet	0.09290304	square meters

1 Introduction

1.1 Background

The U.S. Antarctic Program (USAP) is solely managed by the National Science Foundation (NSF) for the purpose of supporting the United States' national research and discovery endeavors south of 60°S latitude. USAP operates three permanent stations, one of which is at the geographic South Pole (90°S latitude), Amundsen-Scott South Pole Station.

The main facility at the Amundsen-Scott South Pole Station is a 65,000 ft^2, 8.1 million pound, paired C-shaped building elevated above the snow surface by 36 cylindrical columns (Figure 1). The structure was constructed over a multiyear period, owing to the limited outdoor working season (approximately 100 days per year). This resulted in some of the "pods" that make up the large structure being founded on the snow and erected between one and a handful of years after other adjacent pods (Figure 2). Thus, the establishment of dead and live loads for the entire structure was staggered over a long time period, making settlement of the snow foundation under individual columns highly nonuniform. This created a unique challenge for establishing and maintaining a level Station floor.

Figure 1. The elevated Station composing the primary facility at the U.S. Antarctic Program's Amundsen-Scott Station, located at the geographic South Pole.

Figure 2. The elevated Station during construction, showing completed (but unclad) elements and grade beams (snow covered to reduce solar heating), columns, and floor trusses for two not-yet-erected pods.

At their base, each column is attached at an intersection point of a rectangular grid of grade beams (Figure 3). The grade beams in turn rest directly on a variable-width platform of thick, heavy timbers. The timber platform's width at any particular location was selected to attempt to achieve a uniform snow foundation ground pressure beneath the timbers, since a nonuniform normal load is delivered to the grade beams by each of the columns.

Further aiming to create a uniform snow ground pressure, the grade beam network was designed to respond to differential settlement across the grid by increasingly transferring the load from a more rapidly sinking column connection point to adjacent connecting points (Berry and Braun 1999). The designers envisioned the overall building substructure (columns, grade beams, and timbers) would "dynamically" respond to differential settlement so as to not allow the tops of the 36 columns to ever be out of level by more than 2 in. In this way, while perhaps "pulsing" at short time intervals, the entire Station would settle uniformly over periods of years.

Figure 3. Grade beams (rectangular in cross section) and support columns for the elevated Station. Column surveying shown is using a metal tab protruding near top of column as a point of reference (circa 2001).

This analysis takes place using data gathered 17 years after the first columns were set at the end of calendar year 2000. Column settlement monitoring has been performed regularly since then through traditional survey techniques at established points on each of the columns. We have always understood that these surveys took place at a point near the top of each column (Figure 3), and this is supported in a "how to" memo from a multiyear USAP prime-contractor-employed Station surveyor (Kurt Skoog, pers. comm.*). In that document, he states, "The column lugs are located about a foot below the top of the column; therefore, all the shots

* Surveyor for the primary contractor and prepared a 2009 summary of the survey procedures used at South Pole Station, *Summer Monitor Procedures for the New Station*.

on the lugs will be inverted." Further, an annotated image he provided depicts the survey measurement points as we have always understood them (Figure 4). However, the USAP prime-contractor document PMPS-SOP-0076, *South Pole Station Leveling and Raising Procedure*,* states, "Surveys are performed annually at a welded angle near the base of each column supporting the Station." This disagreement in printed documents should be resolved; however, for this analysis, it does not confuse our calculations or conclusions.

Figure 4. The underside of A pods of the elevated Station showing column-height survey points for individual columns ("lugs").

We and USAP senior facilities managers have often discussed routine observations of differential column elevations (i.e., study of the column heights from a single survey event) and have used these observations to guide "shimming" (height adjustments) of one or more columns when there was concern that the elevation difference between adjacent columns would create structural racking damage or interrupt the flow in Station plumbing. However, because such shimming primarily took place at the top of the column where it mates with the floor support truss, these height

* Unpublished internal procedural document.

adjustments occurred above the column survey point. Therefore, future surveys of the columns, while still reflecting the behavior of the column-grade beam settlement in the underlying snow, no longer represented levelness of the Station floor.

1.2 Objectives

In this report, we take a rigorous look at column survey data and shimming, including long-term settlement and adjacent-column height differential trends. We also attempt to predict the near-future state of column heights and Station floor levelness. This was done in part to inform what "shimming" (if any) should have been performed during the 2017–2018 austral summer season at South Pole (November 2017 thru February 2018).

1.3 Approach

Past use and analysis of elevated Station column survey data made the implicit assumption that column height was a surrogate for the floor of the Station. We have become aware that height adjustments have been made (using shims) to the tops of the columns where the Station floor attaches and that these adjustments are not captured by the column surveying protocol. Thus, an accurate understanding of floor levelness does not exist. Our approach in this study is to connect column height survey data with previously inaccessible shimming information to map actual Station floor levelness.

Further, column shimming can, if done without a complete understanding of the foundation design and snow base dynamics, create excess future height adjustment needs. By using long- and short-term trends in column settlement into the snow, we aim to create a model that allows easy visualization of the current state of floor levelness and to predict likely levelness one year hence. We intend to emphasize awareness of the structural foundation design where self-correction of differential settlement rates of adjacent columns is triggered after some degree of offset is reached. We believe this can be observed with a series of recent-past maps of floor levelness.

2 Reference Datum and Assumptions

It is important to point out that the elevation of the survey point on each column is stated with reference to a benchmark at South Pole. Until late 2010, that datum was called the Naval Civil Engineering Laboratory "NCEL benchmark" and was located in an approximately 40 ft deep shaft in the snow floor of the dome that housed the 1975 version of South Pole Station (geodesic dome and metal arches housing Station infrastructure). In 2010, when deconstruction of the dome was imminent, a new "South Pole benchmark" (SPBM) was established some distance directly upwind of the new elevated Station in an area that receives very little vehicle or foot traffic and is more immune to snow drifting that most of the Station campus. This datum is similar to the original benchmark; it is very close to the same subsurface horizon as the NCEL benchmark located deep in a protected snow shaft.

The initial column elevation (height above the active benchmark of the designated survey point on each column) was recorded at the time each family of columns was set in place (Figure 2). This erection was typically associated with assembly of one of the eight pods that make up the elevated Station and usually involved four or six columns. It may be assumed that when the first survey took place, the elevation of the columns recorded at that time corresponded to a level platform upon which the Station floor would be constructed (despite the fact that the recorded column survey heights for that pod were seldom identical). We understand that a level floor was achieved by (a) installing shims between the top of each column and the base of the truss directly supporting the Station floor (Figure 5), (b) jacking up the grade beam and installing a shim between the base or the grade beam and the top of the timber foundation (Figures 5 and 6), or (c) a combination of both. Adjustments were certainly required at the outset since it would have been extremely challenging to prepare the snow foundation and place the timber platform, grade beams, and support columns so as to have the column tops at the same elevation. However, to preserve the assumption of column survey heights being a surrogate for Station floor levelness, it is important to note that future vertical adjustments made at the interface of the grade beam and timber platform automatically become captured as changes in the floor elevation while shimming at the column top and floor truss are not. We believe that the Station designers intended for initial adjustments for out-of-level Station floors to be made by installing shims between the bottom of the grade beam and the top of the timber platform (Figures 5 and 6). Being located below the survey point on each column (and above the survey datum with respect to either of the aforementioned benchmarks), surveys after shimming would automatically recognize the elevation change and thus preserve the relative representation of floor elevation across the entire Station.

The Station designers recognized that snow accumulation (snowfall and snow drifting) would eventually engulf the grade beams and prohibit vertical adjustments by shimming between them and the timber platform. Therefore, the capacity for vertical adjustment was also incorporated at the top of each column (Figure 5). Any postconstruction adjustments to the shim package at the top of a column would not be reflected in column elevation surveys because the permanent survey points are located below the shim packages.

Figure 5. Sketch of the configuration of the support system for the floor of the elevated Station.

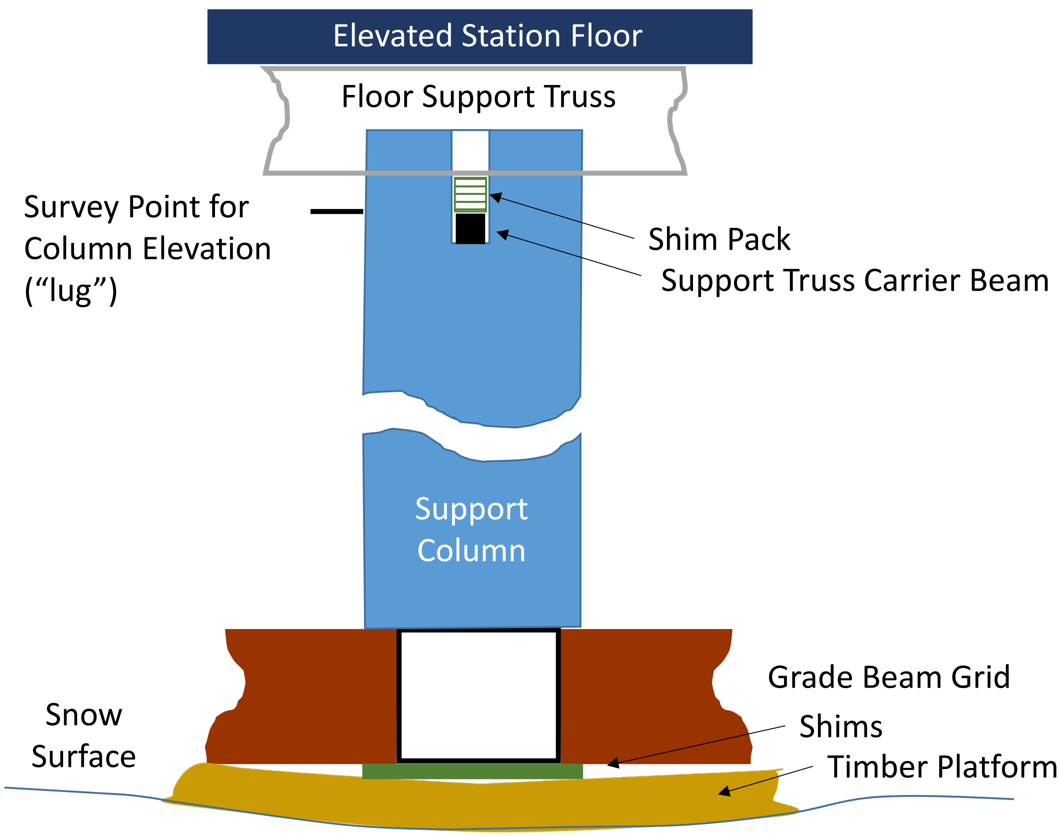
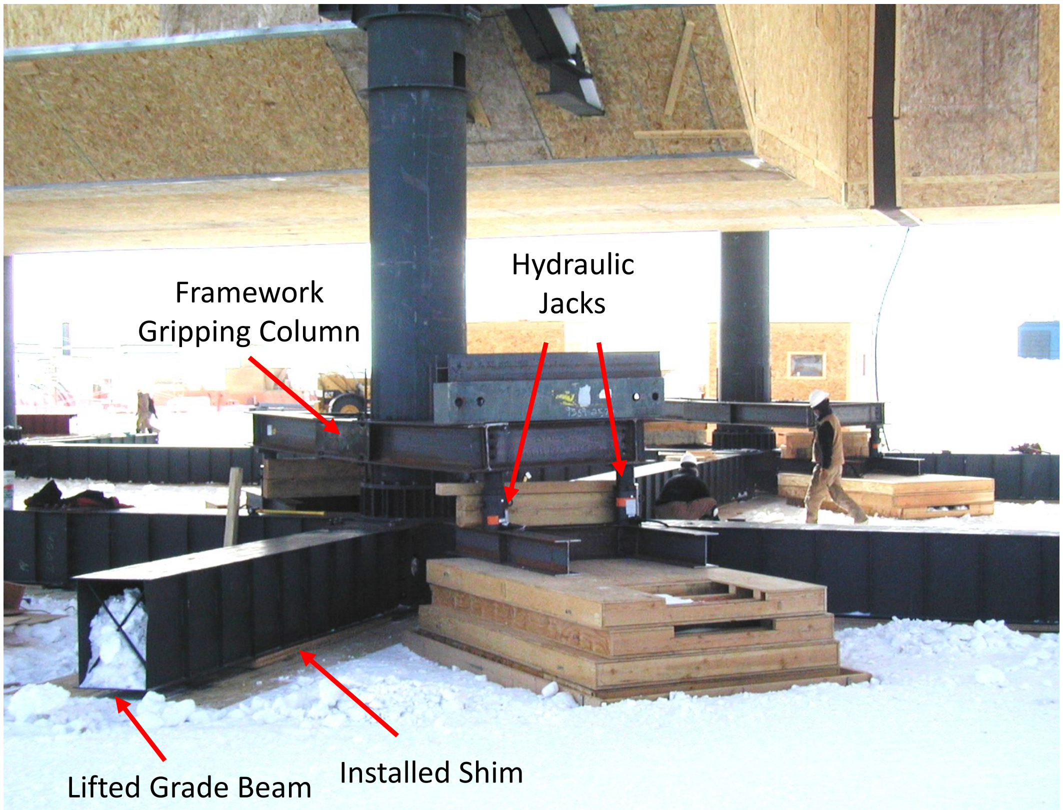


Figure 6. Column lifting and shim placement under grade beam, December 2002.



3 Column Survey Data Analysis

Twenty-five sets of column elevation data spanning 13 years have been added (Table 1) since the last in-depth analysis (Blaisdell and Weale 2006), which included data only up to 31 December 2004. Most years have at least early and late austral summer season data. However, only one set of column elevation survey data exists for the 2013–2014, 2014–2015, and 2015–2016 summer seasons.

No exterior column survey data have been collected during an austral winter; however, between 2004 and 2007, the USAP prime contractor took interior survey measurements of nearly 60 points during the austral winters. We have these data but know little about them. They appear to be referenced to the same benchmark as the summer column survey data but with descriptions such as “punch mark on window sill in room B-1-114,” “top left bolt head of 6 on vertical column S. side B3,” and “underside corner of stair structure B1 above on 1st floor,” we are not able to relate these points to a common datum linked to the Station floor. Thus, they are not useful for this analysis.

The most recent sets of column survey measurements used in this study were taken during the 2016–2017 austral summer on 28 December 2016, 5 February 2017, and 1 December 2017. A curiosity of the 2016–2017 data (Figure 7) is the appearance that some columns (B1-1, B1-2, B1-3, B2-1, A3-3, and A4-3) settled as much as 2 in. (upward curve in Figure 7) over the 38 days between survey data collection while all other columns appear to have moved *upward* on the order of less than ½ in. Both upward movement and sinkage of 2 in. over a month seem improbable to us. However, such disagreement between closely spaced survey data is not new. Blaisdell and Weale (2006) states,

> An odd feature of [the data] is the irregular nature of settlement during the South Pole summer (mid-November to mid-February), when measurements are taken at least monthly. Very few of the column’s data depict a smooth settlement pattern over these four or five closely spaced measurements. We initially suspected that this indicated difficulties for the surveyor(s) in completing a close-tolerance survey under the South Pole conditions. While this may well be a contributing factor, several different surveyors, representing a range of experience levels including a veteran Antarctic surveyor, have executed the measurements (including

> two independent corroborating surveys within a few days of each other), suggesting there are likely other, physical, reasons.

Further, Blaisdell and Weale (2006) speculated,

> Perhaps this is associated with the load sharing that occurs among columns because of the rigid connections to the grade beams in response to differences in settlement. This would be in keeping with the design (Berry and Braun 1999), where "the grade beams . . . act similar to a raft foundation system because it has the stiffness to distribute vertical loads along the grade beam if one area settles more than an adjacent area. This bridging ability to straddle soft areas . . . increases the bearing pressure on stiffer areas, and gives the foundation self-leveling capabilities to limit differential settlement." In this process, it is conceivable that, after some limited period of time, one or more columns nearby may feel enough increase in load to cause an acceleration in their local settlement rate until the load begins to transfer in the opposite direction. Viewed over all the columns, this may appear as if there is a random pulsing of settlement behavior.

We do not think that up to 2 in. of settlement for six individual columns over a 38 day period is explained by the grade beam performing as designed and adjusting to changes in loading from adjacent columns. Nor do we believe that all 30 other columns lifted themselves during the middle of the 2016–2017 austral summer. In fact, over time the overburden associated with the building would consolidate the near-surface snow foundation to the point that these localized, short-interval, accelerated-settlement events would reduce in both number and magnitude. Except for measurement error, we can find no good explanation for this nonintuitive column settlement performance.

Because some of the columns appear to have lifted and some dropped in height, it is not possible to dismiss one date's data over the other. Further, when the 2016–2017 survey data sets are viewed together with the latest survey data (1 December 2017), no clear indication favoring one or the other of the 2016–2017 data is obvious (Figure 7). Thus, for this analysis, we have elected to retain both data sets.

Table 1. Column survey data for South Pole elevated Station used in this study (elevations in feet). The table indicates the use of the Naval Civil Engineering Laboratory (NCEL) benchmark until late 2010 followed by a transition to the South Pole benchmark. The column colors indicated survey measurements collected during the same summer season.

MONITOR	NCEL Benchmark														South Pole Benchmark												
POINT	01/29/05	11/02/05	12/02/05	01/04/06	02/02/06	11/6/2006	02/01/07	11/01/07	02/02/08	10/30/08	01/28/09	10/31/09	01/30/10	***11/02/10***	***11/02/10***	02/01/11	11/07/11	02/01/12	11/12/12	01/21/13	01/06/14	12/19/14	01/01/16	12/28/16	2/5/2017	12/01/17
A1-1	44.19	44.10	44.09	44.06	44.04	43.95	43.93	43.83	43.79	43.61	43.61	43.47	43.40	***43.26***	***43.18***	43.12	42.95	42.90	42.70	42.67	***42.431***	42.19	42.12	41.80	41.81	41.55
A1-2	44.19	44.10	44.08	44.06	44.04	43.94	43.92	43.82	43.78	43.60	43.60	43.45	43.38	***43.24***	***43.16***	43.10	42.92	42.87	42.67	42.64	42.383	42.151	42.07	41.73	41.74	41.47
A1-3	44.15	44.06	44.05	44.03	44.01	43.92	43.91	43.81	43.78	43.61	43.60	43.47	43.41	***43.28***	***43.20***	43.14	42.97	42.92	42.73	42.7	42.452	42.228	42.16	41.83	41.85	41.6
A1-4	44.12	44.04	44.03	44.00	43.98	43.89	43.87	43.77	43.74	43.57	43.57	43.44	43.37	***43.25***	***43.17***	43.11	42.94	42.89	42.7	42.67	42.423	42.211	42.14	41.83	41.84	41.59
A2-1	44.09	44.00	43.99	43.95	43.93	43.83	43.82	43.71	43.67	43.49	43.48	43.34	43.27	***43.13***	***43.05***	42.99	42.82	42.78	42.59	42.56	42.32	42.1	42.01	41.69	41.69	41.44
A2-2	44.08	43.98	43.97	43.93	43.91	43.81	43.80	43.69	43.66	43.47	43.46	43.32	43.25	***43.11***	***43.03***	42.97	42.80	42.76	42.56	42.53	42.288	42.07	42	41.69	41.70	41.45
A2-3	44.12	44.03	44.02	43.99	43.97	43.86	43.84	43.73	43.68	43.50	43.49	43.34	43.26	***43.13***	***43.05***	42.98	42.81	42.77	42.58	42.55	42.303	42.082	41.99	41.67	41.67	41.42
A2-4	44.06	43.96	43.95	43.92	43.90	43.80	43.79	43.68	43.64	43.47	43.47	43.33	43.26	***43.13***	***43.05***	42.99	42.82	42.77	42.58	42.55	42.302	42.091	42.03	41.71	41.72	41.47
A2-5	44.12	44.02	44.01	43.98	43.96	43.85	43.83	43.70	43.66	43.47	43.46	43.30	43.23	***43.09***	***43.01***	42.94	42.77	42.73	42.53	42.5	42.254	42.035	42.01	41.63	41.61	41.37
A2-6	44.12	44.03	44.02	43.99	43.97	43.87	43.85	43.75	43.71	43.53	43.52	43.38	43.31	***43.18***	***43.10***	43.04	42.87	42.82	42.62	42.6	***42.3695***	42.139	42.07	41.76	41.75	41.52
A3-1	44.12	44.02	44.00	43.97	43.96	43.85	43.82	43.70	43.65	43.46	43.44	43.28	43.20	***43.06***	***42.98***	42.91	42.74	42.70	42.50	42.47	42.22	42.00	41.91	41.58	41.57	41.32
A3-2	44.11	44.01	43.99	43.96	43.95	43.84	43.82	43.71	43.66	43.48	43.48	43.32	43.25	***43.12***	***43.04***	42.98	42.80	42.75	42.55	42.52	42.27	42.055	41.98	41.67	41.66	41.42
A3-3	44.10	43.99	43.96	43.94	43.92	43.80	43.78	43.66	43.61	43.41	43.40	43.24	43.17	***43.02***	***42.94***	42.87	42.70	42.64	42.43	42.4	42.137	41.922	41.84	41.57	41.42	41.27
A3-4	44.09	43.96	43.94	43.91	43.89	43.77	43.74	43.60	43.56	43.35	43.33	43.15	43.09	***42.93***	***42.85***	42.78	42.61	42.56	42.35	42.33	42.07	41.84	41.74	41.41	41.40	41.15
A4-1	44.23	44.13	44.12	44.09	44.06	43.97	43.95	43.84	43.79	43.63	43.61	43.46	43.39	***43.26***	***43.18***	43.11	42.94	42.88	42.68	42.65	42.394	42.181	42.1	41.79	41.79	41.55
A4-2	44.20	44.11	44.10	44.06	44.05	43.95	43.93	43.82	43.78	43.62	43.60	43.45	43.38	***43.25***	***43.17***	43.11	42.93	42.88	42.68	42.65	42.385	42.182	42.09	41.78	41.78	41.54
A4-3	44.18	44.07	44.06	44.02	44.00	43.89	43.87	43.75	43.70	43.54	43.52	43.35	43.28	***43.13***	***43.05***	42.99	42.81	42.75	42.55	42.52	42.27	42.04	41.95	41.64	41.59	41.39
A4-4	44.16	44.06	44.05	44.01	43.99	43.88	43.86	43.74	43.69	43.53	43.50	43.34	43.27	***43.12***	***43.04***	42.98	42.79	42.74	42.53	42.5	42.238	42.025	41.93	41.63	41.62	41.38
B2-1	44.12	43.97	43.96	43.93	43.91	43.75	43.71	43.56	43.50	43.31	43.28	43.09	43.02	***42.84***	***42.76***	42.70	42.50	42.44	42.22	42.19	41.917	41.67	41.57	41.37	41.24	40.99
B2-2	44.10	43.95	43.93	43.90	43.89	43.72	43.68	43.51	43.45	43.25	43.21	43.02	42.94	***42.76***	***42.68***	42.62	42.43	42.38	42.16	42.13	41.865	41.621	41.52	41.18	41.20	40.93
B2-3	44.12	43.97	43.95	43.92	43.91	43.74	43.71	43.54	43.47	43.28	43.24	43.05	42.97	***42.79***	***42.71***	42.65	42.45	42.40	42.19	42.15	41.89	41.64	41.53	41.18	41.21	40.94
B2-4	44.15	44.00	43.99	43.95	43.92	43.78	43.75	43.58	43.52	43.33	43.29	43.10	43.02	***42.84***	***42.76***	42.71	42.51	42.46	42.25	42.22	41.951	41.701	41.6	41.30	41.26	41.00
B2-5	43.99	43.83	43.81	43.76	43.73	43.59	43.56	43.41	43.35	43.17	43.13	42.95	42.87	***42.69***	***42.61***	42.57	42.35	42.30	42.09	42.05	41.79	41.57	41.45	41.11	41.13	40.87
B2-6	44.12	44.00	43.98	43.94	43.91	43.79	43.76	43.61	43.55	43.37	43.33	43.16	43.08	***42.92***	***42.84***	42.78	42.58	42.53	42.31	42.28	42.016	41.778	41.71	41.38	41.41	41.15
B3-1	44.21	44.07	44.05	44.01	43.98	43.84	43.81	43.64	43.58	43.38	43.34	43.16	43.08	***42.91***	***42.83***	42.77	42.57	42.52	42.31	42.28	42.015	41.774	41.68	41.33	41.35	41.09
B3-2	44.28	44.15	44.13	44.10	44.07	43.94	43.91	43.75	43.70	43.52	43.47	43.30	43.22	***43.06***	***42.98***	42.92	42.72	42.68	42.47	42.43	42.172	41.931	41.83	41.50	41.51	41.25
B3-3	44.26	44.12	44.10	44.07	44.04	43.90	43.88	43.74	43.68	43.51	43.47	43.30	43.22	***43.06***	***42.98***	42.93	42.73	42.68	42.47	42.44	42.181	41.937	41.85	41.53	41.55	41.29
B3-4	44.23	44.09	44.07	44.03	44.00	43.87	43.85	43.70	43.64	43.47	43.43	43.25	43.18	***43.01***	***42.93***	42.88	42.68	42.63	42.42	42.38	42.13	41.882	41.8	41.47	41.49	41.24
B1-1	44.25	44.12	44.10	44.06	44.04	43.93	43.89	43.76	43.70	43.53	43.49	43.32	43.25	***43.08***	***43.00***	42.94	42.74	42.68	42.47	42.43	42.18	41.929	41.86	41.69	41.55	41.31
B1-2	44.24	44.11	44.10	44.06	44.04	43.92	43.90	43.76	43.71	43.54	43.51	43.33	43.26	***43.09***	***43.01***	42.96	42.76	42.71	42.5	42.46	42.207	41.961	41.86	41.69	41.55	41.29
B1-3	44.15	44.01	44.00	43.96	43.93	43.81	43.79	43.65	43.59	43.43	43.39	43.21	43.13	***42.96***	***42.88***	42.83	42.64	42.58	42.37	42.34	42.078	41.838	41.74	41.57	41.43	41.18
B1-4	44.14	44.01	43.99	43.96	43.93	43.81	43.78	43.63	43.58	43.40	43.37	43.19	43.12	***42.95***	***42.87***	42.81	42.61	42.56	42.35	42.31	42.035	41.81	41.73	41.41	41.43	41.18
B4-1	44.30	44.19	44.17	44.13	44.11	43.98	43.97	43.84	43.78	43.61	43.57	43.41	43.33	***43.17***	***43.09***	43.04	42.85	42.80	42.58	42.56	42.31	42.07	41.99	41.67	41.69	41.44
B4-2	44.37	44.23	44.22	44.18	44.16	44.03	44.02	43.89	43.83	43.68	43.63	43.48	43.41	***43.25***	***43.17***	43.12	42.93	42.89	42.67	42.65	42.396	42.166	42.09	41.77	41.79	41.55
B4-3	44.31	44.16	44.14	44.10	44.08	43.94	43.92	43.78	43.72	43.57	43.53	43.36	43.29	***43.13***	***43.05***	43.00	42.81	42.76	42.54	42.51	42.253	42.021	41.93	41.59	41.61	41.37
B4-4	44.32	44.20	44.19	44.15	44.12	44.00	43.99	43.85	43.79	43.63	43.59	43.43	43.35	***43.18***	***43.10***	43.06	42.86	42.81	42.59	42.57	42.315	42.076	41.98	41.65	41.68	41.42

Placing the post-2004 data together with all prior column survey data (Figure 8) shows that they fit overall with the long-term linear settlement trend established by each column shortly after it received the bulk of its dead load. Thus, despite the apparent curious short-term changes in elevation (within the same austral summer season), the columns continue to follow a predictable and steady penetration into the snow foundation. And, while this is useful for understanding overall Station settlement, it does not provide adequate detail for making conclusions about differential column-pair elevations or Station floor levelness.

The single data set from the 2015–2016 season (taken on 1 January 2016, Figure 8) appears to us to be "offset." This data set shows a major slowing of the settlement trend from the 13 prior years. Suspecting a surveying or reporting glitch, we studied the data briefly. We cannot determine if a "uniform" offset is present; however, the measurements place all columns approximately 5.25 in. higher than would be expected from the adjacent years' data.

We believe that the best predictor of the survey elevation of each column for a future date is linear extrapolation of the elevation data for the immediately prior several years. The graph in Figure 8 (ignoring the 2015–2016 data set) shows justification for this approach. To execute this, we used the series of data sets from late 2012 thru the latest survey on 1 December 2017, leaving out the 1 January 2016 data that appear to be inaccurate (Figure 9). Despite the odd behavior suggested in the two survey data sets from the 2016–2017 summer season (Figure 7), we included both in this analysis. From these seven data sets, we performed a linear regression analysis for each column (Table 2). As would be expected from observing Figure 9, the degree of fit is excellent for each column with an average coefficient of determination, R^2, value of 0.994 (with a standard deviation of 0.005). The slope (or rate of settlement) averaged 0.0006 ft/day (0.0072 in./day) or 2.6 in./year. Settlement rates ranged from a low of 2.54 in./year for columns A1-4 and A2-4 to a high of 2.89 in./year for column B2-3. However, settlement rates are quite consistent over all 36 columns with a standard deviation of 0.000022 ft/day (0.1 in./year), which is well within the survey measurement error (0.01 ft, or 0.12 inches, per USAP prime-contractor-employed Station surveyor Kurt Skoog, pers. comm.).

Table 2. Results of the linear regression analysis on measured column heights between 12 November 2012 and 1 December 2017 and prediction of column survey heights on 1 January 2019.

Column Number	Linear Regression			1-Jan-19
	Slope	Intercept	R^2	Prediction
A1-1	-0.000603	45.336	0.996	41.344
A1-2	-0.000629	45.423	0.996	41.255
A1-3	-0.000594	45.325	0.996	41.389
A1-4	-0.000580	45.231	0.995	41.391
A2-1	-0.000605	45.240	0.997	41.231
A2-2	-0.000581	45.095	0.995	41.251
A2-3	-0.000611	45.252	0.997	41.208
A2-4	-0.000580	45.110	0.995	41.271
A2-5	-0.000611	45.204	0.997	41.158
A2-6	-0.000583	45.177	0.997	41.314
A3-1	-0.000622	45.223	0.997	41.104
A3-2	-0.000593	45.138	0.996	41.214
A3-3	-0.000619	45.132	0.992	41.036
A3-4	-0.000637	45.143	0.998	40.925
A4-1	-0.000594	45.270	0.996	41.340
A4-2	-0.000599	45.293	0.996	41.327
A4-3	-0.000620	45.260	0.998	41.156
A4-4	-0.000604	45.165	0.996	41.167
B2-1	-0.000628	44.960	0.985	40.802
B2-2	-0.000649	44.999	0.996	40.699
B2-3	-0.000661	45.073	0.997	40.700
B2-4	-0.000655	45.111	0.996	40.778
B2-5	-0.000644	44.900	0.997	40.638
B2-6	-0.000609	44.964	0.994	40.931
B3-1	-0.000647	45.137	0.997	40.855
B3-2	-0.000642	45.271	0.997	41.021
B3-3	-0.000621	45.181	0.995	41.068
B3-4	-0.000622	45.132	0.996	41.011
B1-1	-0.000583	45.005	0.979	41.143
B1-2	-0.000609	45.152	0.981	41.122
B1-3	-0.000602	44.995	0.981	41.010
B1-4	-0.000612	45.009	0.994	40.956
B4-1	-0.000604	45.222	0.995	41.223
B4-2	-0.000594	45.268	0.996	41.332
B4-3	-0.000623	45.261	0.997	41.137
B4-4	-0.000621	45.310	0.996	41.197
AVE	-0.000613	ft/day	0.994471	
St Dev	0.000022		0.004811	

Figure 7. Change in total settlement of all columns supporting the elevated South Pole Station during the past three surveys, focusing on the two surveys conducted 38 days apart during the 2016–2017 austral summer season.

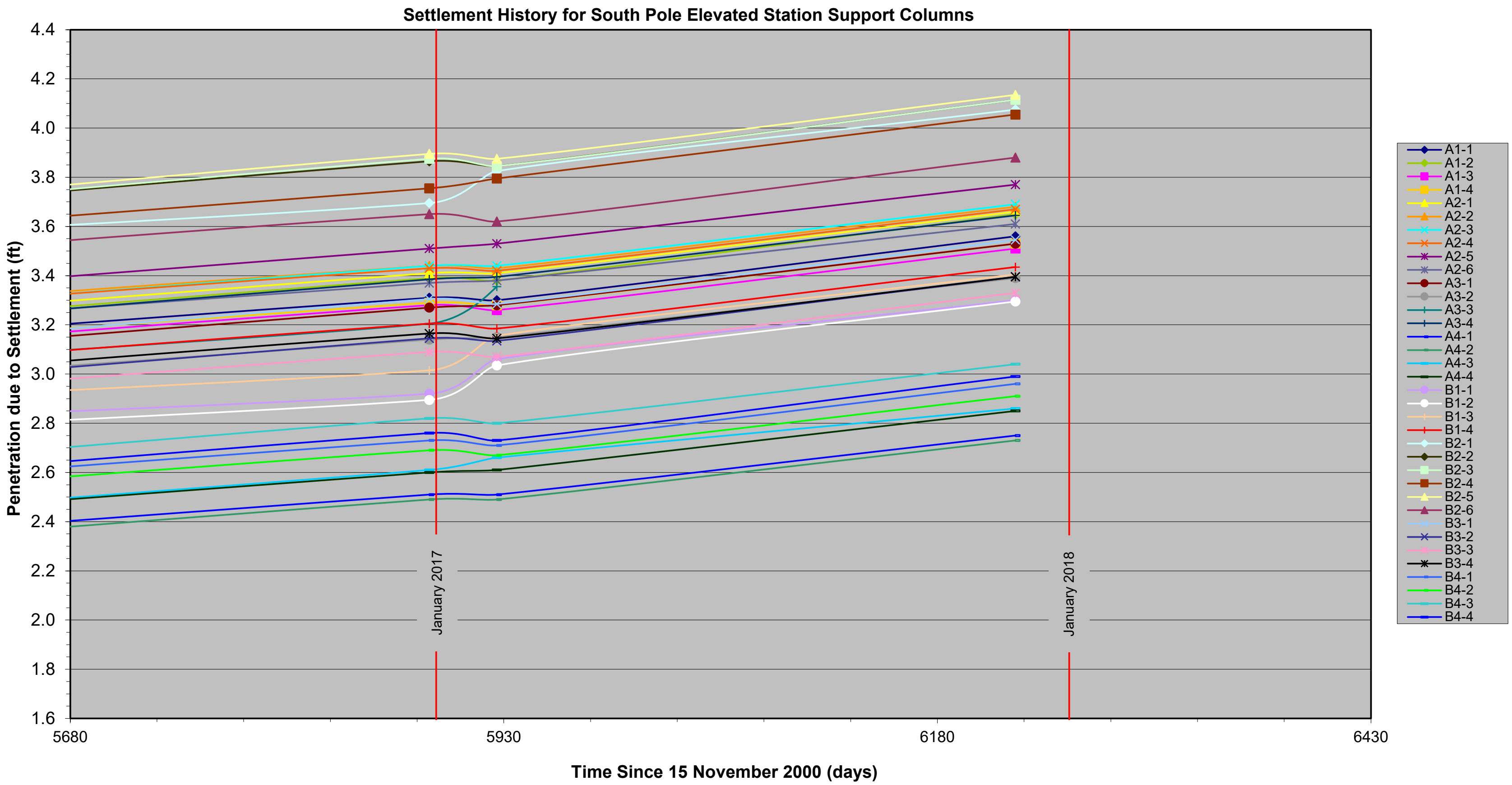


Figure 8. Progression of total settlement of all columns supporting the elevated South Pole Station between the time they were initially installed and the 1 December 2017 survey.

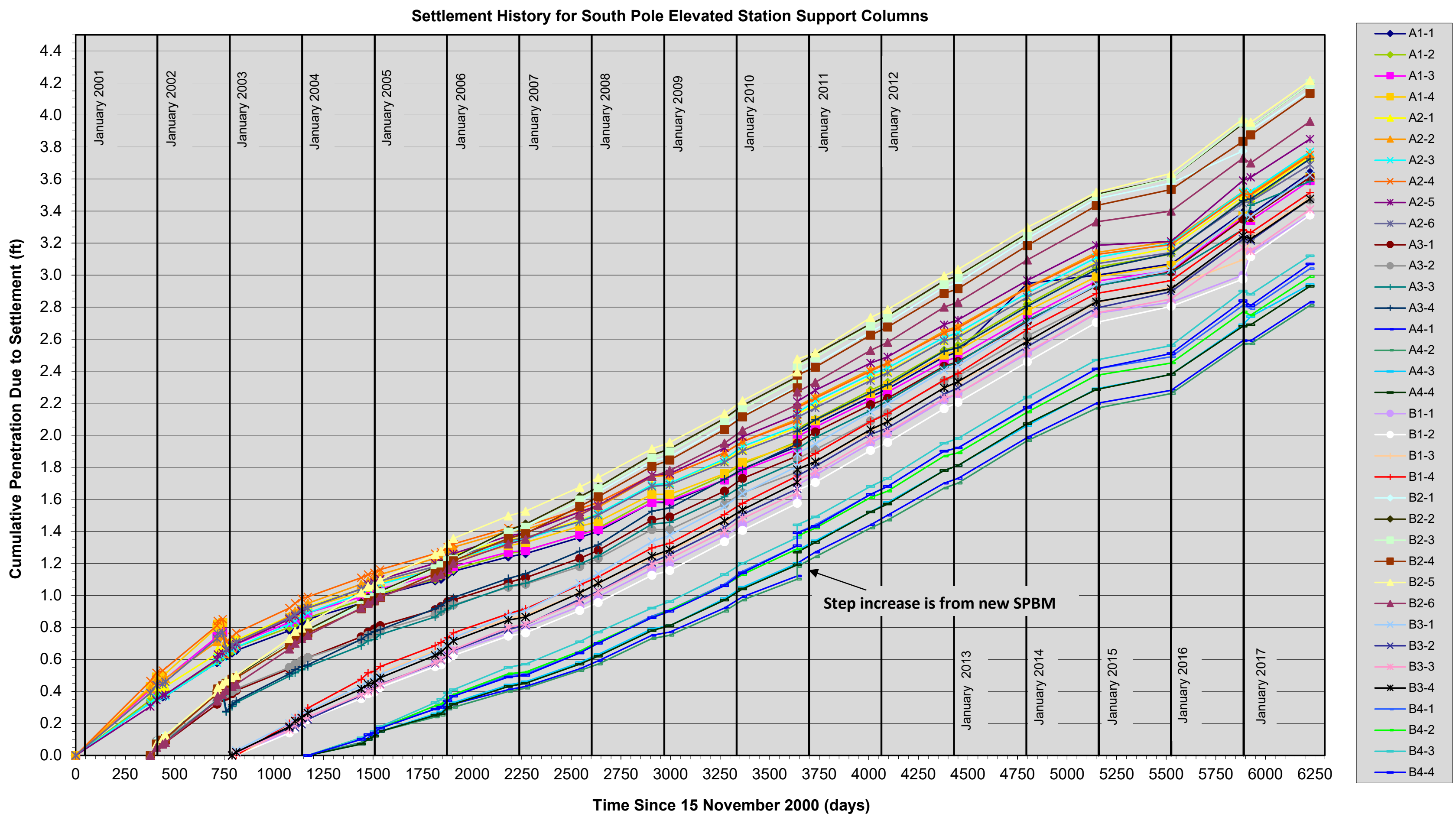
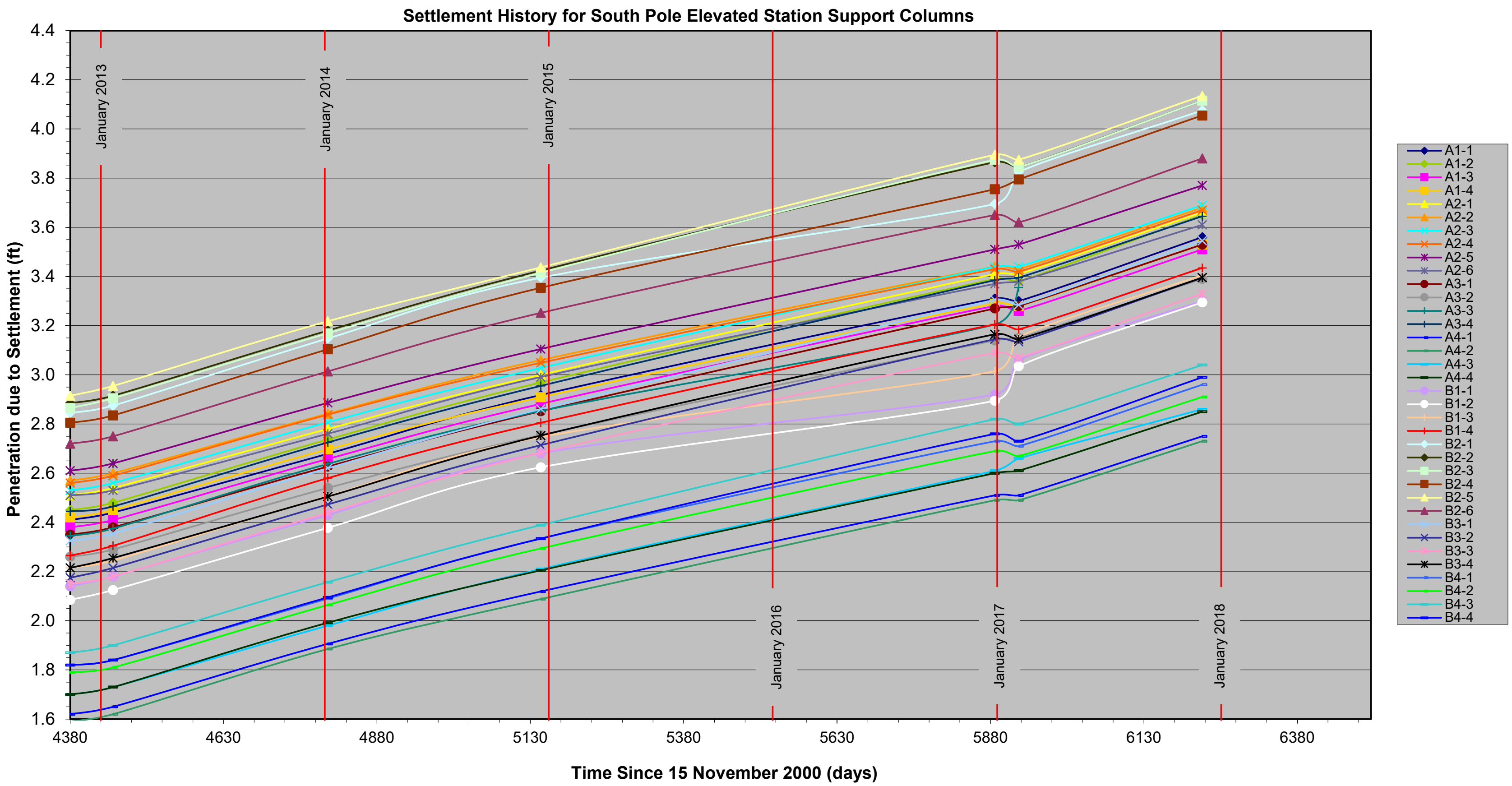


Figure 9. Data used for the linear regression analysis to allow prediction of January 2019 elevation of support columns.



4 Station Floor Levelness

In the past, we took the accumulated differential settlement data from column surveys to be a direct indicator of the levelness of the floor of the elevated Station. This approach assumed that whatever thickness of shims was present at the top of each column when the Station floor was initially set remained fixed throughout time. However, we now know that adjustments to the column-top shim pack have been made. (In January 2015, columns B2-6, B1-4, and B1-1 were adjusted, respectively, by removing 0.75 in., 1.25 in., and 1.5 in.) Unfortunately, it does not appear that a full historical documentation of these shimming activities is available. Thus, the assumption is not valid that column survey data can be used to determine Station floor levelness.

Elevated Station floor levelness, not column settlement (although the two are strongly linked), is the topic of most import as it bears on the performance of doors, windows, wall panels, plumbing grades, and other structural health issues. Not having a reliable or complete record of all shimming and other building-to-foundation height adjustments, we could not make any conclusions about the levelness of the elevated Station floor or make recommendations for the location or thickness of shims required to create and maintain a level floor system from any of the existing survey data. To ameliorate this, we requested that field personnel perform a "measuring tape" data collection at each column to obtain an accurate measurement of the distance between the base of the column survey "lug" and the base of the truss directly supporting the elevated Station floor (Figures 5 and 10). This required creating a small access hole in the bottom of the fairing surrounding each column top but ultimately took minimal effort and likely will not cause any long-term issues. These measurements (Table 3), when combined with the column survey data, allow the elevated Station floor to be related to a single datum (SPBM) at 36 locations.

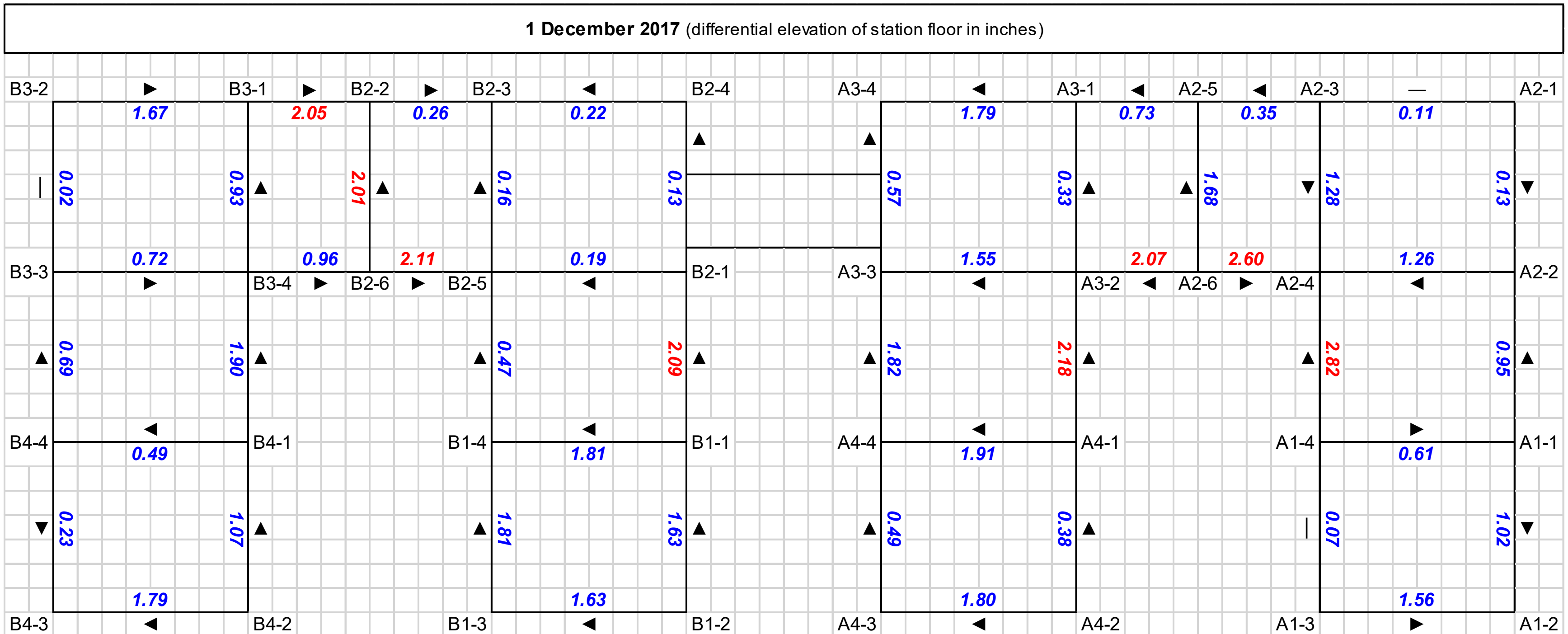
Adding the surveyed column heights to the measured distance from the survey point to the base of the floor-support truss allowed us to generate a "map" of floor levelness (Figure 11). Fortunately, the majority of the Station floor appears to be level within the 2 in. differential limit established by the building designers. Only eight of the fifty column-pair connections exceed 2 in. (four in pods A and four in pods B); and of those, only two are more than 0.2 in. over the limit. Further, the two pairs more than 0.2 in. over the limit (A2-4/A2-6 and A1-4/A2-4) are less than 3 in. different in height and are adjacent to each other, making adjustment easier.

Figure 10. Hole drilled in the bottom of a column top fairing (*top*) to allow measurement of the distance between the base of the column survey lug and bottom of the floor support truss (*bottom*).

Table 3. The measured vertical distance between the base of the column survey "lug" and the base of the floor truss directly supporting the elevated Station floor.

MONITOR POINT	Dec-17	
	inches	feet
A1-1	56.000	4.67
A1-2	55.938	4.66
A1-3	55.938	4.66
A1-4	56.125	4.68
A2-1	56.500	4.71
A2-2	56.250	4.69
A2-3	56.625	4.72
A2-4	54.750	4.56
A2-5	56.875	4.74
A2-6	56.750	4.73
A3-1	56.750	4.73
A3-2	55.875	4.66
A3-3	56.125	4.68
A3-4	57.000	4.75
A4-1	56.500	4.71
A4-2	57.000	4.75
A4-3	57.000	4.75
A4-4	56.625	4.72
B2-1	55.500	4.63
B2-2	56.125	4.68
B2-3	55.750	4.65
B2-4	55.250	4.60
B2-5	56.750	4.73
B2-6	55.500	4.63
B3-1	56.250	4.69
B3-2	56.000	4.67
B3-3	55.500	4.63
B3-4	55.375	4.61
B1-1	53.750	4.48
B1-2	55.625	4.64
B1-3	55.313	4.61
B1-4	53.500	4.46
B4-1	54.875	4.57
B4-2	54.625	4.55
B4-3	55.000	4.58
B4-4	54.625	4.55

Figure 11. Elevation differences in the floor of the South Pole elevated Station between adjacent support columns on 1 December 2017. *Italicized* numbers represent difference in elevation in inches. *Blue* numbers are within the designers' established limit of 2 in. *Red* numbers represent column pairs with more than 2 in. difference in elevation. *Arrows* indicate the direction of slope (high to low), and *dashes* indicate essentially level column pairs.



5 Shimming Decision Support

A straightforward and simplistic approach to address floor levelness would be to adjust the eight column pairs that show more than 2 in. of difference in elevation. However, as we have noted, our experience with the settlement of the Station columns suggest the foundation design may need more than 2 in. of differential settlement to fulfill its self-adjusting function. Thus, we do not believe there exists a sense of urgency for six of the eight column-pair locations with over 2 in. of elevation difference. However, because the opportunity to make adjustments is essentially only once per year, it is important to understand the rate of change of differential elevation between column pairs with more than 2 in. of offset before deciding to postpone adjustment.

To test this approach, we produced floor levelness maps for each of the column surveys after the 1 January 2015 shim adjustments (to the best of our knowledge, no adjustments have been made since then). These three maps (Figures 12, 13, and 14) for 5 February 2017, 28 December 2016, and 1 January 2016 plus the map for the most recent survey (1 December 2017, Figure 11) allow us to check for trends in column-pair locations. (Despite discarding the 1 January 2016 data earlier when generating regressions for predicting future column survey heights, we use the data here, recognizing that, by itself, it likely represents an accurate comparison of all column heights on a single date.) For the eight column-pair locations of concern on 1 December 2017 (Figure 11), over the 23-month period since the 1 January 2016 survey (Figure 14), some of these eight locations show a steadily increasing height differential, others have a pulsing height differential (growth and reduction), while still others appear to have a stable difference in height. Table 4 summarizes our observations.

Figure 12. Elevation differences between adjacent South Pole elevated Station support columns on 5 February 2017. *Italicized* numbers represent difference in elevation in inches. *Blue* numbers are within the designers' established limit of 2 in. *Red* numbers represent column pairs with more than 2 in. difference in elevation. *Arrows* indicate the direction of slope (high to low), and *dashes* indicate essentially level column pairs.

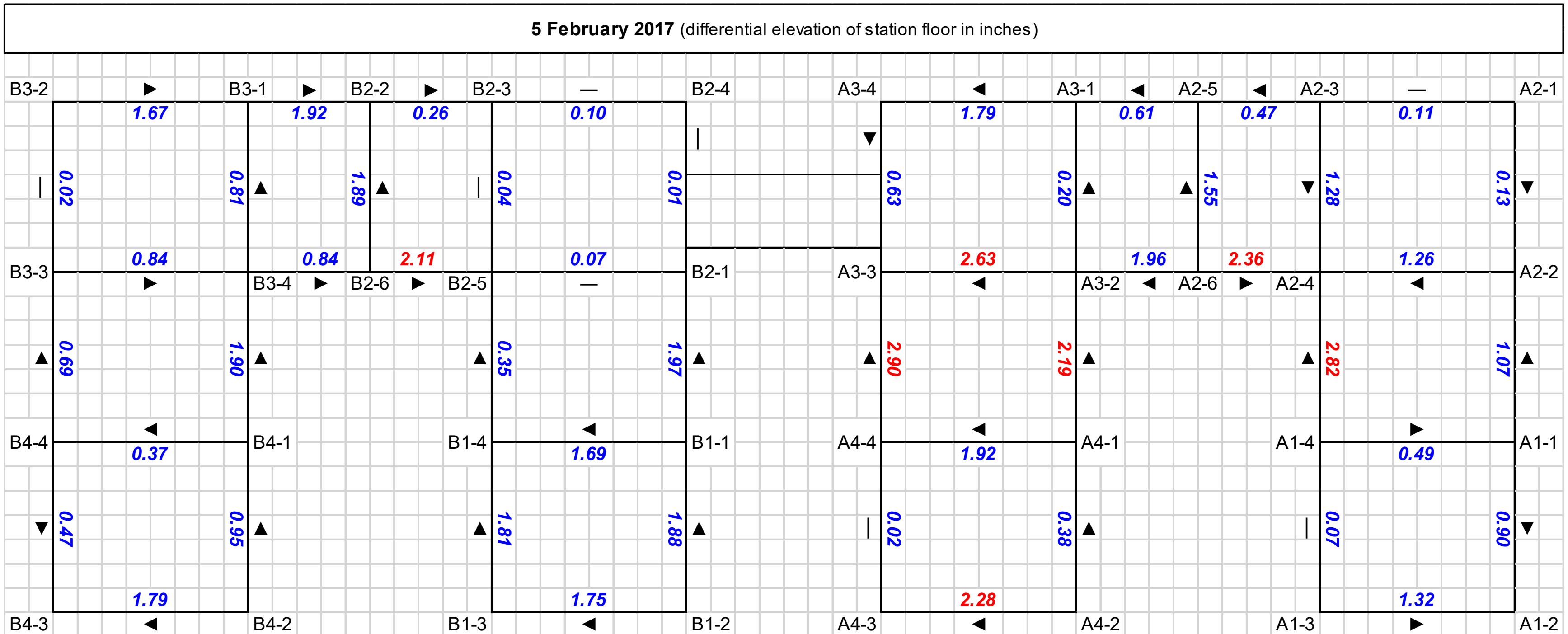


Figure 13. Elevation differences between adjacent South Pole elevated Station support columns on 28 December 2016. *Italicized* numbers represent difference in elevation in inches. *Blue* numbers are within the designers' established limit of 2 in. *Red* numbers represent column pairs with more than 2 in. difference in elevation. *Arrows* indicate the direction of slope (high to low), and *dashes* indicate essentially level column pairs.

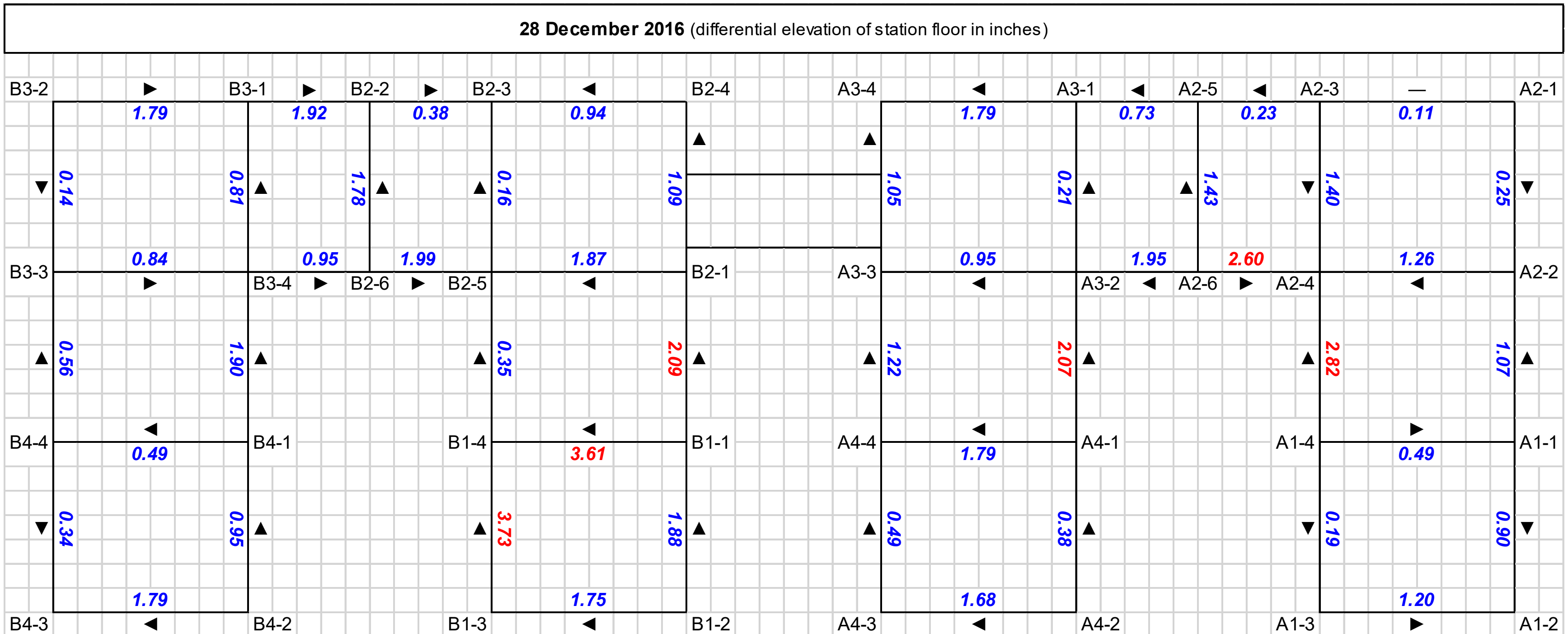


Figure 14. Elevation differences between adjacent South Pole elevated Station support columns on 1 January 2016. *Italicized* numbers represent difference in elevation in inches. Blue numbers are within the designers' established limit of 2 in. *Red* numbers represent column pairs with more than 2 in. difference in elevation. *Arrows* indicate the direction of slope (high to low), and *dashes* indicate essentially level column pairs.

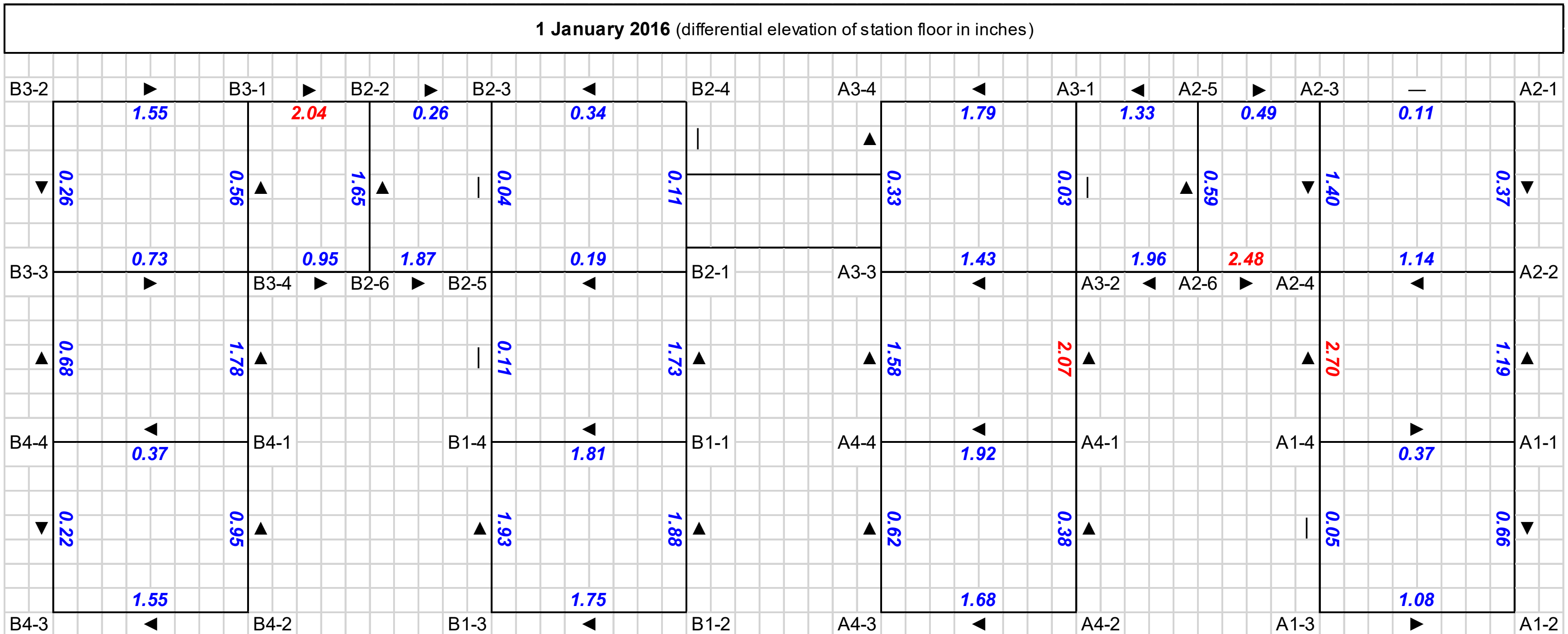


Figure 15. Predicted elevation differences between adjacent South Pole elevated Station support columns on 1 January 2019. *Italicized* numbers represent difference in elevation in inches. *Blue* numbers are within the designers' established limit of 2 in. *Red* numbers represent column pairs with more than 2 in. difference in elevation. *Arrows* indicate the direction of slope (high to low), and *dashes* indicate essentially level column pairs.

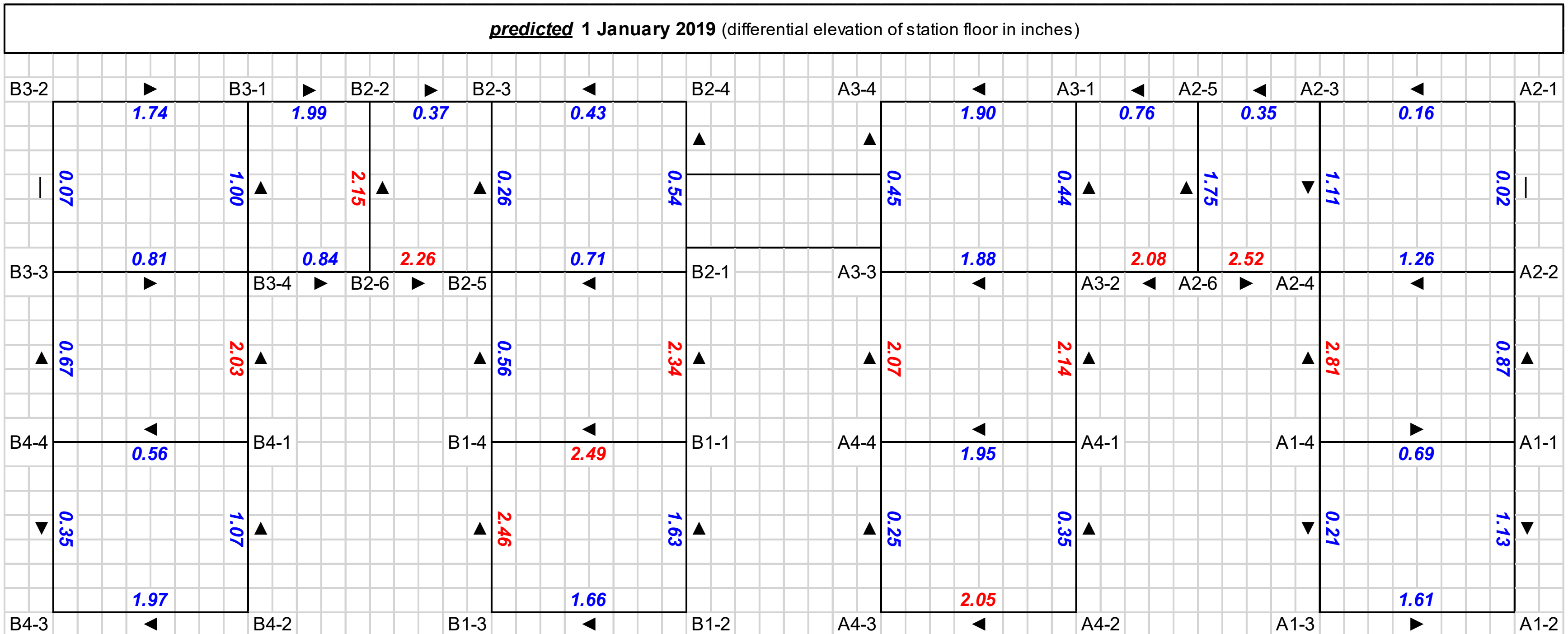


Table 4. Differential height activity over 1 January 2016 to 1 December 2017 for eight column pairs showing more than 2 in. of differential elevation on 1 December 2017.

Column Pair		Observed Behavior
A1-4	A2-4	Unchanging
A2-4	A2-6	Pulsing
A2-6	A3-2	Slowly increasing
A4-1	A3-2	Recent small increase
B1-1	B2-1	Pulsing
B2-5	B2-6	Slowly increasing
B2-2	B2-6	Slowly increasing
B2-2	B3-1	Pulsing

Using the column-height prediction for 1 January 2019 (Table 2) and assuming no shim adjustments took place during the 2017–2018 summer season, we made a floor levelness prediction for the middle of the 2018–2019 summer season (Figure 15). This shows the possibility of 12 column-pair locations that would exceed 2 in. of differential height. Seven of the twelve we predicted are the same pairs showing too much offset now (1 December 2017, Figure 11), five new pairs with over 2 in. difference were added, and one column pair shifted back under 2 in. The latter is pair B2-2/B3-1, which we noted to be pulsing in its height differential (Table 4). Four of the five new pair locations predicted to have over 2 in. offset on 1 January 2019 (Figure 15) can be seen to have a pulsing (A3-3/A4-4 and A4-2/A4-3) or erratic (B1-1/B1-4 and B1-3/B1-4) behavior over the past four surveys (Figures 11–14). The fifth pair (B3-4/B4-1) shows stable offsets over this time period but is predicted to slightly top 2 in. of differential elevation by next season. This consistency is encouraging but perhaps not surprising considering the approach we used to predict column elevation heights (linear regression over the past several years) and the unchanging column-top-to-Station-floor distances.

The two column pairs showing erratic behavior (B1-1/B1-4 and B1-3/B1-4) show a nearly 2.5 in. predicted offset in January 2019 (Figure 15). This is a nearly ¾ in. change over the coming year and may be alarming. Certainly, it calls for scrutiny as a candidate for column-top adjustment. However, we note that these two column pairs are less than 2 in. offset now (Figure 11) and also were on surveys 11 months earlier (5 February 2017, Figure 12) and 23 months ago (1 January 2016, Figure 14). Curiously, these column pairs were over 3.5 in. offset in the 28 December 2016 survey (Figure

13), just a month before being less than 2 in. offset in the 5 February 2017 survey (Figure 12). While we cannot explain why there seem to be rapid, wild settlement pulses with these two column pairs, observing their past behavior causes us to be only marginally concerned with the 1 January 2019 predicted offsets. Continued observation is needed to see if an explanation can be discovered.

6 Recommendations

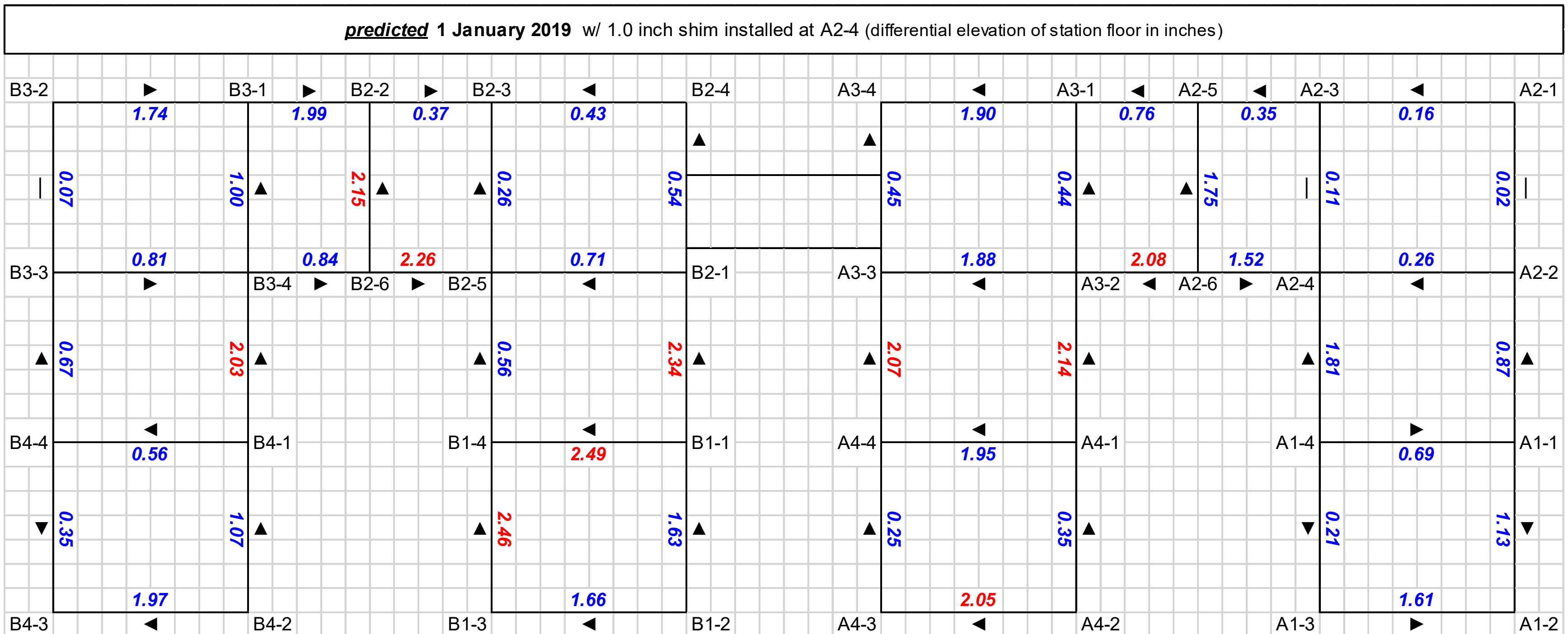
After calculating Station floor levelness at the time of the most recent survey (1 December 2017, Figure 11), we believe only two column pairs require adjustment: A1-4/A2-4 and A2-4/A2-6. While six other column-pair locations show more than 2 in. of differential height now, they are all just over the 2 in. limit. Further, our prediction for floor levelness a year into the future (1 January 2019) shows one location likely going back under 2 in. of offset and the other five locations to only diverge in elevation by a small amount (less than 0.3 in.). And this prediction supports making adjustments at the A1-4/A2-4 and A2-4/A2-6 locations since neither column pair shows much change over the next 12 months.

Our recommendation for remedying the two column-pair locations that we believe should be adjusted is to perform shimming at the top of column A2-4 only. By lifting the floor truss in this location by 1.0 in., both column pairs will be well within the 2 in. limit, and the other two adjacent connecting column-pair locations (A2-4/A2-3 and A2-4/A2-2) will be positively impacted (decreased differential heights) (Figure 16). Following shim insertion, we recommend remeasuring the vertical height from the lugs to the base of the truss to update the value.

We suggest that column surveys be conducted at least once per year. Further, the survey data should be compared to past data to observe if the measurements are consistent with historical trends and data troubleshooting or a resurvey executed if a result such as was seen in January 2016 is observed. To assist in determining survey accuracy, some statement should be included in the transmitted result indicating the survey closure value (difference between first measured point and that point measured again at the end of the survey event).

Lastly, it is vital that an accurate and archived record of shim adjustments be maintained together with column-height survey data. This will allow Station floor levelness to be easily determined for each column survey date. Additionally, it will enable accurate accounting for long-term trends of column-pair behaviors. Implementing these recommendations will enhance the functionality and productive life span of the Station.

Figure 16. Predicted elevation differences between adjacent South Pole elevated Station support columns on 1 January 2019 if a 1 in. shim is installed on the top of column A2-4 during the 2017–2018 summer season. *Italicized* numbers represent difference in elevation in inches. *Blue* numbers are within the designers' established limit of 2 in. *Red* numbers represent column pairs with more than 2 in. difference in elevation. *Arrows* indicate the direction of slope (high to low), and *dashes* indicate essentially level column pairs.



References

Berry, D., and F. Braun. 1999. Foundation Design for the Elevated Station at Amundsen-Scott South Pole. In *Cold Regions Engineering: Putting Research into Practice, Proceedings of the 10th International Conference*, 16–19 August, Lincoln, NH, ed. J. E. Zufelt, 82–93. Reston VA: American Society of Civil Engineers.

Blaisdell, G. L., and J. C. Weale. 2006. *Settlement of a Foundation on a Permanent, Deep Snowpack*. ERDC/CRREL TR-06-03. Hanover, NH: U.S. Army Engineer Research and Development Center.

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
June 2019

2. REPORT TYPE
Special Report/Final

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Analysis of Recent Support-Column Survey Results for the Elevated Facility at Amundsen-Scott South Pole Station

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
George Blaisdell, Jason Weale, and Lynette Barna

5d. PROJECT NUMBER

5e. TASK NUMBER
EP-ANT-18-06 & EP-ANT-18-20

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Engineer Research and Development Center (ERDC)
Cold Regions Research and Engineering Laboratory (CRREL)
72 Lyme Road
Hanover, NH 03755-1290

8. PERFORMING ORGANIZATION REPORT NUMBER
ERDC/CRREL SR-19-3

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Science Foundation, Office of Polar Programs
2415 Eisenhower Avenue
Alexandria, VA 22314

10. SPONSOR/MONITOR'S ACRONYM(S)
NSF-OPP

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
Engineering for Polar Operations, Logistics, and Research (EPOLAR)

14. ABSTRACT

The snow-based foundation for the large elevated Station at Amundsen-Scott South Pole Station is continuously migrating (creep) away from the load imparted by structure's support columns and grade beams. Because of nonhomogeneities in the snow foundation, differential loads on each support column, and the facility's approximately 10-year build-out and progressive-occupancy period, nonuniform settlement of columns is occurring. The created differences in the tops of the columns, where the Station's floor is attached, can cause serious structural damage and interfere with utilities.

Following up on our previous (2006) review of the history of column settlement, this report incorporates essential ancillary measurements and assesses actual Station floor levelness. We determine that past actions to mitigate differential column settlement by shimming at column tops has and continues to be adequate to maintain an acceptable floor levelness. Further, we present a model for predicting future measures of floor levelness that can help facilitate decisions about when and what columns to shim to best preserve resources.

15. SUBJECT TERMS
Amundsen Scott South Pole Station (Antarctica), Buildings, EPOLAR, Foundations--Cold weather conditions, NSF, Settlement, Snow mechanics, Snowpack, Survey measurements

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER *(include area code)*
Unclassified	Unclassified	Unclassified	SAR	42	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18